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ABSTRACT

The range in aluminum of the deuterons accelerated by the 184-inch cyclotron has been measured. The energy deduced from the range-energy curves of J. H. Smith[5] is 196 Mev which is in excellent agreement with the expected value. Range measurements at the same energy have also been made for Be, C, Cu, Mo, Ag, Sn, Pb, and U. These results agree well with as yet unpublished theoretical curves prepared in this laboratory. Approximate measurements of the energy loss per cm path have also been made for these materials relative to aluminum.

INTRODUCTION

The theory of the energy loss of charged particles passing through matter resulting from ionization and excitation of the atoms and molecules has been developed by Bethe and others.[1] These investigations lead to the following expression for the energy loss per cm path

$$\frac{dE}{dx} = \frac{4\pi N Z_1 Z_2^2 e^4}{mv^2} \left[\ln \frac{2mv^2}{(1-\beta^2)I} - \beta^2 \right]$$

where m is the electron mass, v the velocity of the ion of atomic number Z_2, Z_1 the atomic number of the absorbing material containing N atoms per cm^3, I is the average excitation energy of the atoms in the absorber, and e and β have their usual significance. Two principal uncertainties arise in the application of this formula. In the first place, for velocities v of the order of the orbital velocities of the electrons in the K shell, we cannot assume that all of the electrons per cm path (NZ_1) contribute their full share to the energy loss. The necessary corrections to equation 1 to take account of this effect have been discussed by Livingston and Bethe.[1] In the second place the quantity I has to be determined by calculation or experiment and this proves to be of considerable difficulty. Fortunately, especially for high velocities, the energy loss does not prove to be very sensitive to this quantity. It has been suggested by Bloch[2] that I may be expressed in the form $I = KZ_1$, where K is a constant. Through analysis of experimental data of Wilson's,[3] Wheeler has proposed that (expressed in electron volts) $I = 11.5\ Z_1$, and this is the value commonly adopted. Recent measurements by Tsien San-Tsiang,[4] however, suggest a value of I for air ($Z = 7.22$) of 100 ev, considerably above that predicted by Wheeler's expression or the value 80.5 ev adopted by Livingston and Bethe. It should also be noted that the proportionality between I and Z_1 should hold better for higher values of Z_1.

Using this theory, and $I = 80.5$ ev for air and 150 ev for Al, Smith[5] has calculated by numerical integration range-energy relations for air and aluminum to proton energies of 10,000 Mev. Similarly, the theoretical group in this laboratory, under the direction of Professor R. Serber, has calculated range-energy curves for a number of substances.[6]

Experimental verification of these conclusions has of necessity in the past been limited to velocities in the neighborhood of 3×10^9 cm/sec. Since we how have available deuterons of velocity 1.2×10^{10}

cm/sec, it is desirable to check the predicted curves at this energy. While the results obtained are not of very great accuracy, it seems desirable to publish them at this time since they provide a measurement of the energy of the deuterons produced by the 184-inch cyclotron, and since other experiments with the cyclotron utilize range measurements as a measure of energy.

EXPERIMENTAL PROCEDURE

Since the complete deflector system required to bring the ion beam clear of the cyclotron magnetic field was not available at the time of these experiments, it was necessary to work with the internal beam. Use was made, however, of the pulsed electrostatic deflector[7,8] which displaces the center of the orbit by two or three inches, causing the beam to clear its former path by this amount in the vicinity of the probe target. In this deflector the ion beam expands into an electrode system of angular length about 120° consisting of four copper bars placed in electrically connected pairs above and below the plane of rotation of the ion beam. When the ions have reached the appropriate radius (as determined by the frequency of the oscillator) a radial electrostatic field was produced by the electrodes so directed as to deflect the ions to smaller radius. The target is placed near the start of the deflector since it may be shown that the maximum radius of the ions will be obtained at this point. Auxiliary experiments have shown that near the median plane an essentially parallel beam of ions is obtained over an area of several square inches.

The deflected beam was incident upon a block of the material to be investigated of width 3 inches and height 3/4 inches. The rear surface of the block was machined at an angle of 8° 8′ with respect to the front surface, the mean thickness being chosen to coincide with the expected range of the deuterons (Figure 1). The maximum thickness of material traversed by the beam was indicated by the line of demarcation between exposure and non-exposure produced on a strip of X-ray film placed against the rear face. For relative measurements between aluminum and another material, two such blocks were mounted one above the other with coplanar rear surfaces and recording on a common strip of film. When the range in aluminum was substantially greater than the range in the other material, the latter was divided into a number of strips so that it occupied the same total volume as the aluminum standard. No similar division of the aluminum was made, however, for the cases (Be and C) in which the range in aluminum was less than in the material. A fiducial mark was photographed upon the film while in the holder to facilitate relation of the observed cut-off of the beam to the edge of the block. In many of the exposures (which were about 3 secs) a film was placed in front of the block to verify that the entire assembly was uniformly irradiated with deuterons—this was found to be always the case.

RANGE MEASUREMENTS

Using this method, a total of 70 range measurements in aluminum have been made, of which 45 were made without a monitoring film in front of the block. The mean of these latter measurements is 7.018 cm with a probable error on a statistical basis of 0.003 cm. Using our determination of the density (2.715 gm/cm^3) and the range energy relation of Smith we arrive at a maximum energy of the deuterons of 196.2 Mev. From the radius at which the center of the entrance of the electrostatic deflector was set (81.2 inches) and the value of the magnetic field at this radius (14,210 oersteds) a value of 195 Mev is obtained. Since the deflector channel is 1 inch wide, and the uncertainty in the setting may be 0.2 inches, and in addition an uncertainty in the radius of about 1 inch may arise from radial oscillations of the ions which are known to occur, the agreement is very satisfactory.

For the measurement of the ranges in other materials, the results are based upon four or five measurements for each substance. In all cases a correction was applied to reduce all measurements to a common range in aluminum (7.018 cm). This adjustment was made on the assumption that the range is proportional to some power of the energy and that the exponent is independent of the atomic number.

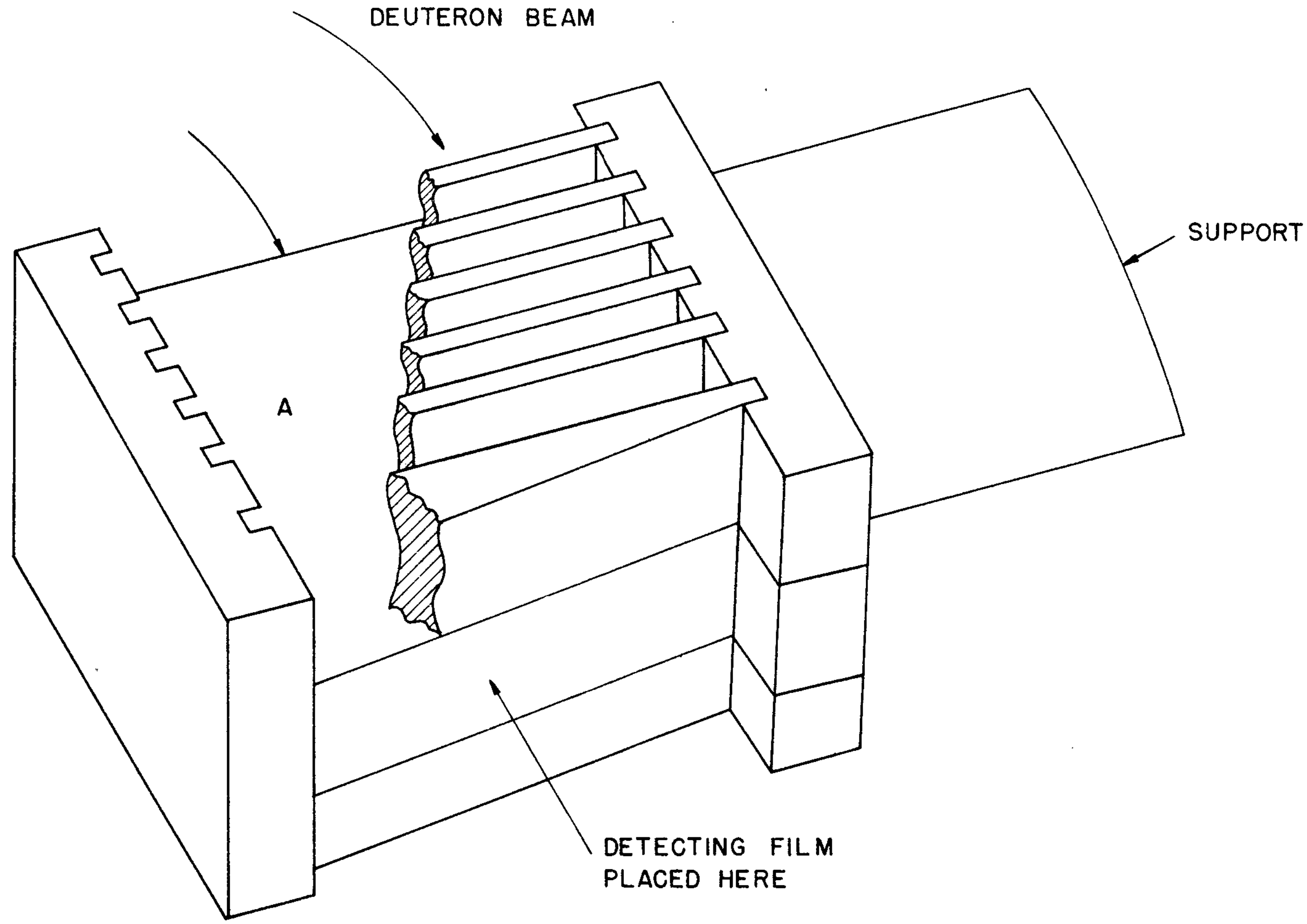

Figure 1. Sketch of range measuring device. The aluminum block used as a standard is indicated by A, and above it is shown a typical arrangement of absorbers of a material of greater stopping power per cm than aluminum. To minimize background radiation, the entire assembly when in use was encased in $\frac{1}{2}$-inch lead with the exception of the side facing the incoming deuterons. A vacuum lock permitted easy withdrawal of the assembly.

Thus $(\Delta R/R)_{Al} = (\Delta R/R)_x$, and from the measured departures of the aluminum range from the mean value, a corresponding correction was calculated for the observed range in the material under investigation. This correction was in all cases less than 1.5%. The results are presented in Table 1 together with our measured values of the densities of the various materials. Also presented in Table 1 are theoretical ranges, for a deuteron energy of 197 Mev furnished by Aron, Hoffman, and Williams.[6] In the final column are given values, relative to Al = 1, of the average stopping power per electron averaged over the full energy range; S is defined by the relation $S = \left(\frac{\text{Range} \cdot Z}{A}\right)_{\text{aluminum}} \left(\frac{\text{Range} \cdot Z}{A}\right)_{\text{material}}$, where the range is in gm/cm^2 and Z and A are the atomic number and atomic weight respectively.

Table 1. Experimental and theoretical ranges for deuterons and average stopping power per electron relative to Al.

Material	Density (gm/cm^3)	Adjusted range (gm/cm^2)	Theoretical range (196.2 Mev) (gm/cm^2)	S
Be	1.862	17.38	18.75	1.16
C	1.613	16.39	17.0	1.12
Al	2.715	19.05	Standard	1.00
Cu	8.839	22.81	22.85	0.882
Mo	10.16	25.21	25.44	0.832
Ag	10.44	25.62	26.12	0.823
Sn	7.239	27.10	27.33	0.804
Pb	11.29	31.63	32.17	0.734
U	17.88	32.52	33.82	0.731

It is believed that the density values in Table 1 are accurate to about 1%. Spectrochemical analysis showed that impurities were not a significant source of error. Examination of the experimental range determinations shows that maximum departure of an individual measurement from the mean value for that material is 0.7%. An attempt has been made to estimate the limits of possible errors in the range measurements, these vary between ± 1% for the lighter elements to ± 5% for uranium; it is believed that these limits are conservative.

As pointed out by Wilson,[3] it will be noted from Figure 2 that a linear relation apparently exists between S and the logarithm of Z. In view of the wide velocity range involved it does not seem possible to attach much theoretical significance to this relation although it is clear that it should be approximately valid. It should also be noted that the experimental points of Wilson (measured at $v > 3 \times 10^9$ cm/sec) do not fall on the same line. It would appear possible, however, on an empirical basis, to predict the range, relative to aluminum, of ions of this velocity in any element with ease and moderate accuracy by the use of this relation.

MEASUREMENT OF DE/DX

In an attempt to measure the energy loss per cm path at these energies, range measurements were repeated at a lower energy. It is not possible with our present arrangements to reduce the energy of the deflected cyclotron beam, and accordingly the energy of the deuterons was reduced by interposing a known thickness of aluminum. These measurements are thus purely relative to aluminum, the energy

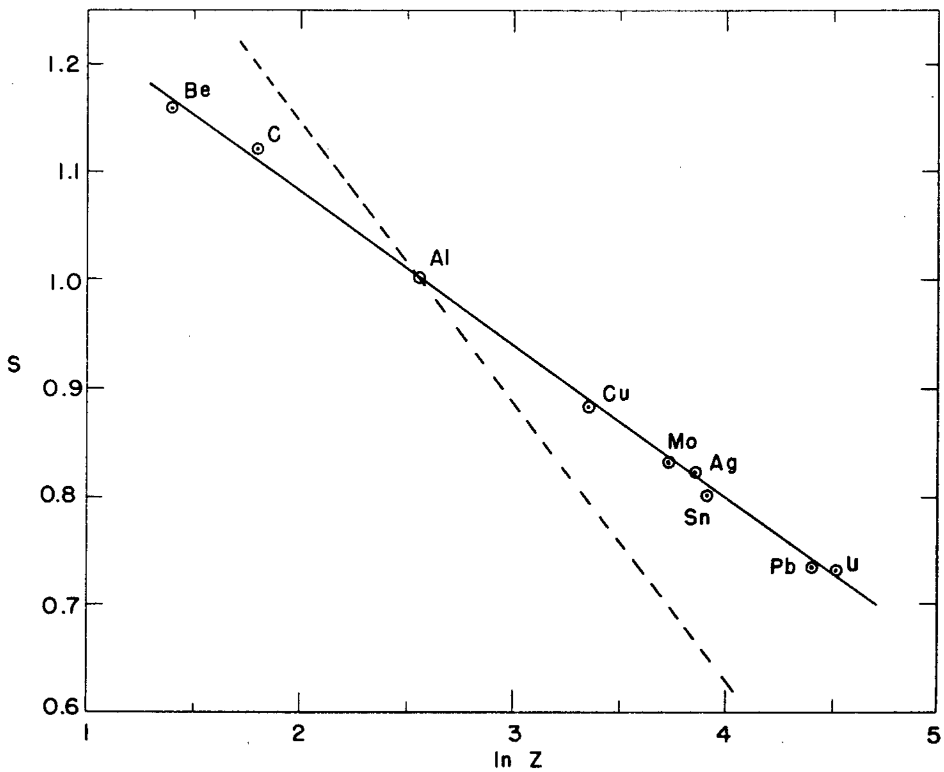

Figure 2. Experimental relation between the average relative stopping power per electron, S, averaged over the energy range 0−200 Mev and relative to Al = 1, and the atomic number, Z, of the absorber. The dotted line indicates the results obtained by R. R. Wilson at 2−4 Mev and adjusted to Al = 1.

Table 2. Experimental values of Δx and $\Delta E/\Delta x$. The energy loss was inferred from a theoretical range-energy relation for aluminum. Theoretical values of $\Delta E/\Delta x$ are also included.[6]

Substances	x (gm/cm²)	$\Delta E/\Delta x$ Mev per gm/cm² Exp	theor	
Be	1.54	8.31	7.54	I = 72 ev
C	1.80	7.11	6.97	I = 89 ev
Al	2.14	5.98	6.02	I = 11.5 ~~Z~~ ev
Cu	2.69	4.76	5.10	"
Mo	2.78	4.61	---	"
Ag	2.79	4.58	4.48	"
Sn	3.25	3.94	---	"
Pb	3.61	3.55	3.67	"
U	3.54	3.62	---	"

loss being determined by Smith's calculations. The thickness introduced was 2.145 gm/cm^2 which corresponds to an energy loss of 12.8 Mev. Table 2 gives the measured changes in range together with the value of (dE/dx) (Mev per gm/cm^2) obtained. From the estimated limits of error referred to the previous section, these may be in error by as much as 15% in the worst cases. It is hoped that it will be possible to repeat these measurements with greater accuracy with an external beam at a later date.

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